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Current status, future expectations and mitigation potential scenarios for China's primary aluminium industry

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Abstract

Over the past three decades, China has undergone a strong economic growth, largely industry-driven. The rise of consumption resulted in increasing material requirements like steel, cement, plastic and aluminium. Regarding aluminium, the in-use stock increased to 58.9 kg/capita in 2009, from around 8.5 kg/capita in 1989 and 19.4 kg/capita in 1999. China's role in the aluminium industry is crucial. On its own, it produces around half of the world's primary aluminium output, destined for both domestic consumption and international export markets. However China's domestic bauxite reserves are limited and at current static exploitation would last for only 18 more years. Considering the low quality of its bauxite and the young and relatively low in-use stock level, China has to rely mainly on primary production, by heavily depleting its bauxite resources and by importing foreign bauxite and alumina. Primary aluminium production takes however a high environmental toll. This paper evaluates the effect of changes in: energy efficiency due to the technological level of both electricity and aluminium production, quality of resources and share of secondary and primary production; on the environmental impact due to the Chinese primary aluminium sector, by means of forecasting scenarios and mitigation potentials.

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Keywords: Primary aluminium; electricity; China; LCA.

1. Introduction

In this paper the environmental damage caused by primary aluminium production in China is estimated for 2020 and three scenarios are developed to identify potential mitigation efforts. The situation in China is of peculiar interest because of the country's unique strong growth over the last decades. According to the World Bank [1] its Gross Domestic Product (GDP) grew from US$356 billion in 1990 to US$1.199 billion in 2000 and US$5.930 billion in 2010. Meanwhile, its population grew but at a slower pace and amounted to 1.360 million in 2010 [2]. The people steadily got richer, improving living standards and consumption levels. Modern Chinese consume manufactured goods like cars, foils and cans, building space, electronics and aircraft in strongly increasing volumes. As a result, the in-use stock of aluminium grew to 58kg/capita in 2009 [3], up from about 10kg in 1990 and 20kg in 2000 [4]. The growth of in-use stock was mainly supplied by primary aluminium production. Secondary production is still relatively low in China as the in-use stocks are young compared to the average life time of aluminium products (which is 16 years according to Yue et al. (2014) [5]) and because the logitics required for efficient recycling in China are not yet fully developed. Most of the additional in-use stock in China consists of construction materials, engineering machinery and transportation means [3,5]; all of which have long to very long life times. Our impact analysis shown that in 2012 the average CO_2 density of primary aluminium production in China was 19.24kgCO_2/kg. In comparison, the global average CO_2 density of secondary aluminium production is 1.45kgCO_2/kg, or 92.5% less than for primary production in China. As China has limited access

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to secondary aluminium production, it is compelled to rely on the heavily polluting primary source.

The primary aluminium production processes studied in this paper are the extraction of bauxite ore, the refining of bauxite ore into alumina and the electrolysis of alumina into molten aluminium. Refining is a mainly fuel-based process, to supply the large quantities of heat, while the electrolysis is a mainly electricity consuming process. The Ecoinvent dataset v3 were used as an main Life Cycle Inventory (LCI) source [6]. According to the USGS [7], China produced about 22Mtonnes of primary aluminium in 2013, or about 46% of the global output. In comparison its factories only churned out 8.6Mtonnes of secondary aluminium that same year [7-8]. This paper focus on the global warming potential expressed in CO_2eq. emissions of all integrated processes in order to facilitate the comparison of the results with those from literature.

Primary production of aluminium affects the environment in both direct and indirect ways. The implemented production technology and bauxite quality are examples of endogenous factors while the electricity production technology and electricity mix are examples of exogenous factors. These affect the energy efficiency and carbon density of the studied processes. This paper evaluates the effect of changes in the aluminium production technology, the electricity production technology and mix, bauxite quality and share of secondary production on the future environmental impact of the Chinese aluminium industry. Starting from the situation in 2012, three scenarios are defined for 2020. At first the Best Available Technology (BAU) scenario is analysed (A), followed by two mitigation scenarios (B and C). Future trends in the above characteristics are extracted from various studies of the Chinese aluminium and electricity industry [9-11]. Future production volumes in China are estimated through a regressive forecast taking into account the country's expected population [2] and GDP growth [12].

2. Current situation

2.1. Material flows

To supply its primary aluminium industry, China produces about 50% of the required bauxite domestically, and imports the other half. In 2013 the remaining bauxite reserves in China equaled 830Mtonnes [13], enough to last around 18 more years at current extraction rates. Chinese bauxite is mostly of the diasporic type, which contains relatively more silica then the rest of the lateric type. Unfortunately, diasporic bauxite requires much more energy intensive refining processes than lateric bauxite. In order to cope with the lower bauxite quality, China heavily relies on imported lateric bauxite and developed specialised processes for refining silica-rich ores. In 2013 China refined 44Mtonnes of alumina [14], or about 43% of the global output. In that same year it produced 22Mtonnes of primary and 8.6Mtonnes of secondary aluminium [7-8]. On average the primary production grew slightly stronger between 2012-13 than dictated by the 12th Five-Year-Plan [14]. It set the limit at 8.6% while output grew by 8.8%. The growth of bauxite, alumina, primary and secondary production volumes in China between 2000-13 is shown in figure 1.

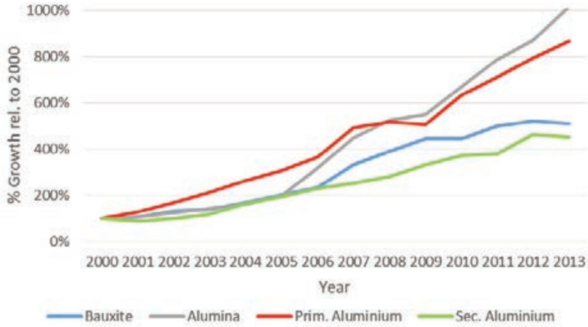
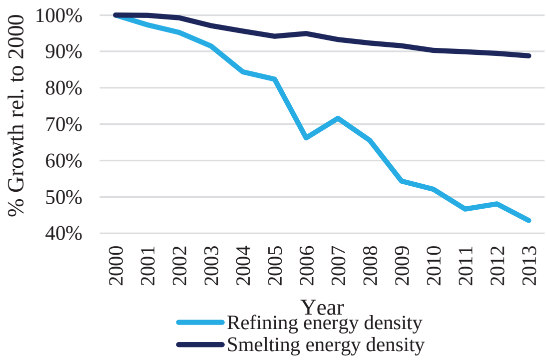


Figure 1: Relative growth of bauxite, alumina, primary aluminium and secondary aluminium production in China since 2000 (in %, 2000=base year). Source: USGS, IAI [7-8, 14].

2.2. Aluminium production technology

Bauxite extraction requires almost no energy compared to refining and smelting, it is hence excluded from the explicit analysis. Refining is a heat-intensive process and its main heat source are fossil fuels. China's average refining energy density has been rapidly decreasing over the last decade from 10kWh/kg to about 4.3kWh/kg in 2013 [15] (Figure 2). The average energy density however remains above the global average, mainly because of the share of low-grade bauxite in its raw material mix. As briefly stated above, China has been busy developing special refining processes to increase its energy competitiveness compared to diasporic bauxite refiners. According to Zhang et al. (2014) [11], refining diasporic bauxite with the classical Bayer process results in 2-4 times higher energy densities. The Lime Bayer Process (LBP) and Ore Dressing Bayer Process (ODBP) are typical examples of alternative processes, but they however result in about 40% higher bauxite consumption.

Figure 2: Evolution in energy density of refining and primary smelting



processes in China (in %, 2000=base year). Source: IAI [15].

The electrolysis energy density has steadily been decreasing too, from 15.5kWh/kg in 2000 to 13.7kWh/kg in 2013 [16] (Figure 2). It quickly became smaller than the global average due to its late-mover advantage: Chinese production plants incorporate more recent technology (e.g. Point Feed Prebake) than older European plants. Continuous engineering and economies of scale imposed by the government (horizontal integration) allowed an average improvement of 1% per year [11, 15]. Despite having a competitive electricity intensity thanks to recent technology, Chinese producers still have a lot of margin for improvement. This is mainly because the industry is not concentrated and hence many plants do not have access to economies of scale.

2.3. Electricity production

An estimated 4.700TWh of electricity were used by the Chinese primary aluminium industry in 2011, which is about 5.3% of the national electricity consumption (based on the National Bureau of Statistics of China [16]). A study by Lin et al. (2015) [17] estimated this figure at 4.9%, which is lower due to a lower estimation of the electrolysis electricity density. There exist 6 different electricity grids in China, each characterised by a different electricity mix. As a consequence, average carbon densities ranged between 0.65-0.98kgCO_2/kWh [11]. Northern provinces tend to rely more heavily on coal than southern provinces, where hydropower is available. Hence the geographical location of primary aluminium smelting plants has an important influence on the total CO_2 they produce. In 2012 the average Chinese electricity mix consists of about 75% of fossil sources (mostly coal), 17% hydro and about 4% nuclear and wind [16]. Most coal plants are still of the sub-critical type, characterised by low efficiencies. Due to the nationwide building frenzzy of the last decades, many electricity plants are too small to access favourable economies of scale. Similarly to the aluminium production facilities, the government is taking action to increase this industry's concentration.

3. Future expectations in China

3.1. Primary aluminium production

The production forecasting model is based on the country's population and GDP, hence it is relevant to provide insight in these two factors' expected changes until 2020. China's population is expected to grow to 1.40-1.47 billion by 2020 for low to high fertility according to the United Nations [2]. China's GDP will increase from US$9.24 trillion in 2012 to US$14.55 trillion by 2020 according to estimation by HSBC [12]. The growth of population and GPD are shown in Figure 3 and 4 respectively. Feeding these data into the forecasting model developed in this paper yields expected alumina, primary and secondary aluminium production volumes. The ranges for low – medium – high fertility are shown in Table 1. These will be used for all three future scenarios A-B-C).

Table 1: Forecasted alumina, primary and secondary aluminium production volumes in 2020 in China.

	Scenario A	Scenario B	Scenario C
Alumina [Mt]	66.1 – 68.4 – 70.6		
Primary aluminium [Mt]	31.0 – 33.3 – 35.7		
Secondary aluminium [Mt]	12.8 – 13.7 – 14.6		

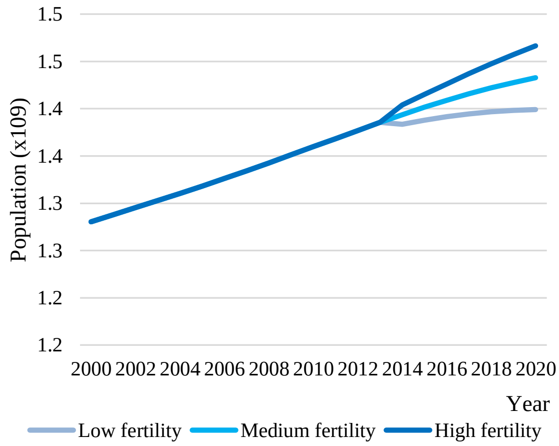


Figure 3: Expected population in China by 2020 for low, medium and high fertility (in billions). Source: UN [2]

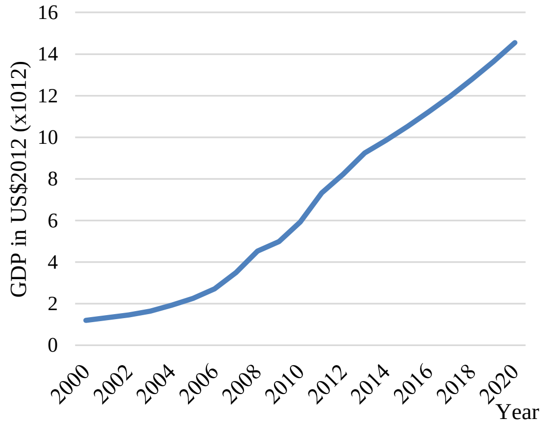


Figure 4: China's expected GDP (in trillions of US$2012). Source: HSBC [12]

3.2. Electricity production and energy mix

In the mid-term future (i.e. 2020) China's main power source is expected to remain coal. However, it is realistic to assume that China will increase its renewable and nuclear capacity and upgrade the existing technology in coal-fired plants in order to increase their efficiency and emissions. Based on studies by Liu et al. (2009) [9] and Cai et al. (2007) [10], different future scenarios can be developed with different electricity mixes and technologies. The following paragraphe briefly describes the expected developments. For further details, please refer to [9-10] and the Five-Year-Plans [14].

In the baseline scenario (A), the current situation is largely maintained with only few changes. The mix remains very coal-driven and sub-critical coal-fired processes are only rarely upgraded to super- or ultra-supercritical level.

Renewables get only little attention and remain marginal. In the medium mitigation scenario (B), the electricity industry increases in concentration allowing for scale effects to be exploited, Integrated Gasification Combined Cycle (IGCC) technology is implemented in new plants and renewables receive more support. In the strong mitigation scenario (C) all the above are implemented but at a higher degree, supercritical technology breaks through and Carbon Capture and Storage (CCS) and nuclear power are also playing a role. The government also plays a more important role in pushing for new technologies through legislation and subsidies. According to [10] the expected carbon desnities of the wholesale electricity in China can be estimated at the values shown in Table 2 for the different scenarios.

3.3. Refining and smelting technology mix

As previously stated, the alumina refining and aluminium smelting processes are subject to increasingly strict supervision and regulation by the Chinese government (cf. Five-Year-Plans). It hopes to stimulate continuous efficiency progress by imposing external pressure on the aluminium industry: close down small capacity plants and have many others merge, decrease the subsidies on electricity to force smelters to rethink their electricity usage and finally by setting strict entry-limits concerning size, efficiency, emission. Besides, increasing the average plant scale by eliminating smaller plants makes it easier to collect data and monitor material flows, electricity consumption and emissions.

Zhang et al. (2014) [11] developed several scenarios in which they forecast the energy densities of both processes in the future. For refining, they define scenarios with varying industry concentration, increasing lateric bauxite imports and upgrades (and restrictions) in the process technology (from the Lime-Soda Sinter Process (LSSP) and Sinter-Bayer Combined Process (SBCP) towards LBP and ODBP).

In the smelting stage, they suggest various degrees of phasing-out of the remaining Söderberg processes, increased industry concentration, higher external pressure on efficiency and even geographical relocations for access to cheaper electricity.

The precentage decrease of the refining energy density was retained and applied on the 2012 values. Table 2 provides an overview of the estimated carbon density of the refining process and the electricity density of the smelting process in 2020 in China.

Table 2: Estimated carbon density of the refining process and the electricity density of the smelting process in 2020 in China [11]; and expected carbon desnities of the wholesale electricity in China in 2020 ($kgCO_2/kWh$) [10].

	Scenario A	Scenario B	Scenario C
Refining carbon density [$kgCO_2/kg$]	2.74	2.59	2.57
Smelting electricity density [kWh/kg]	12.61	12.43	11.27
$kgCO_2/kWh$ in 2020	0.77	0.73	0.66

The table 3 gives a recap of the assumptions in electricity, alumina and primary aluminium production evolution until 2020 for the different scenarios.

Table 3: Recap of assumptions made for each scenario concerning the electricity, alumina and primary aluminium production evolution until 2020.

	Scenario A	Scenario B	Scenario C
Electricity mix	Old coal-fired technology remains (subcrtical) with a slow introduction of SC and USC. Renewables are also only slowly growing.	SC, USC and IGCC grow faster although subcritical coal-fired plants remain present in the mix. Renewable sources like wind and solar power receive more governement support than in A.	All subcritical coal-fired plants have been replaced with modern SC or USC. IGCC has grown a lot and renewables benefit extra governement support. Nuclear technology also undergoes further growth.
Technology mix	<u>Refining:</u> LSSP and SBCP keep being used next to LBP and ODBP as limited high grade bauxite ore is imported. No big changes in average scale. <u>Smelting:</u> average 1% decrease of electricity intensity per year due to slow scale improvements and further Söderberg discontinuation	<u>Refining:</u> stricter regulation imposes LSSP and SBCP to be phased-out by 2020 and the scale is imporved. <u>Smelting:</u> stricter regulation and growing electricity prices boost increasing efficiency efforts along with increasing scale	<u>Refining:</u> stricter regulation than in B accelerates the phase-out of LSSP and SBCP and increases the scale faster, bauxite imports grow. <u>Smelting:</u> even more efforts than in B under increased external pressure

4. Results

Applying all data from tables 1-3 on the LCIA model in SimaPro results in nine different future CO_2 emission estimations for the Chinese primary aluminium industry: three scenarios times three population fertilities. Figure 5 presents the total CO_2 produced for each of these along with the value for 2012.

All future scenarios predict total CO_2 emissions above the 2012 level, which is in line with intuition. For medium population fertility, the business-as-usual scenario (A) yields an emission of 584Mt of CO_2, or 52% more than in 2012. Bearing in mind that the total primary production volume increases by 62% between 2012-20, the carbon density of the production process decreases, which is in accordance with the estimations put forward in table 2-3. Continuing in the medium fertility dimension, it is visible that the mitigation scenarios provide a substantial mitigation potential, with scenario C being stronger than scenario B. Scenario B only results in a 44% increase in total emissions compared to 2012, while scenario C forecasts a 29% increase. For low and high population growth, the expected emissions are respectively lower and higher than for medium growth. This is logical as these scenarios predict respectively lower and higher absolute production volumes.

Figure 6 present the breakdown of the mitigation potential of scenarios B and C (i.e. the difference between the CO_2 emissions of scenario B and C compared with A) for medium fertility. From these the important difference between both mitigation scenarios is accentuated.

Scenario B suggests a 33Mtonnes of CO_2 reduction, that consists of about 69% of savings in the smelting stage. These savings are mainly due to the cleaner electricity used in the smelting process. By contract, only 13% of the mitigation potential of the refining process is electricity-related: most savings in the refining process stem from increased process performance and as a consequence a decreased use of fossil fuels for the heat supply.

In scenario C the mitigation potential is about 89Mtonnes of CO_2, almost 3 times more than in scenario B. In this case about 87% of the mitigation potential stems from the smelting process, which is 18%pt more than in scenario B. This difference can be explained by the much cleaner electricity mix in scenario C combined with an even lower electricty denssity of the process itself.

An important driver for the mitigation potential in the refining process in China that was not really taken into account in these scenarios is the quality of the used bauxite ore. The amount of bauxite required in the classical Bayer Process is about 28% lower than in the the LBP process, which is used to treat high silica ores. Additionally, the energy density of the classical Bayer Process is 2-4 times higher when diasporic bauxite is used compared to lateric bauxite. Hence a larger ration of lateric/diasporic bauxite used in Chinese refineries could result in an important additional emissions reduction. The relocalisation of primary aluminium melters to regional grids with high hydro power penetration can yield additional savings of indirect emissions.

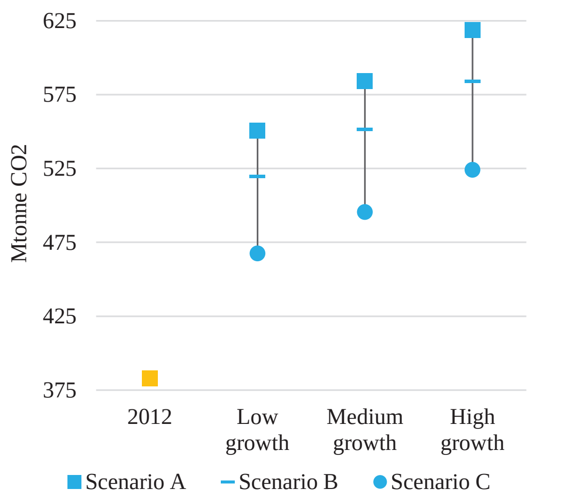


Figure 5: Forecasted total CO_2 emissions from the Chinese primary aluminium industry (mining excluded) in 2020 for scenarios A, B and C and for low, medium and high fertility ($MtCO_2$).

CO_2eq. emissions also have to be considered. Most of the non-CO_2 molecules amongst them stem from the electrolysis, which is usually conducted in a fluorite bath. These emissions were not included in the above analysis, but they usually represent about 15% of the total CO_2eq. emissions. Electricity consumtpion reduction, more optimised PFP software and better exhaust gas cleaning can help to strongly decrease their emissions. Carbonless electrodes would even preempt them alltogether.

As a last point, it is crucial to underscore the importance of secondary aluminium. At 13 times lower specific CO_2 emissions than its primary counterpart, increasing its share in the total production volume offering the strongest mitigation potential of all available production technologies, scale benefits or engineering performances. The world will yet have to wait for China's Al in-use stock to grow and age and for its recycling logistics to further develop.

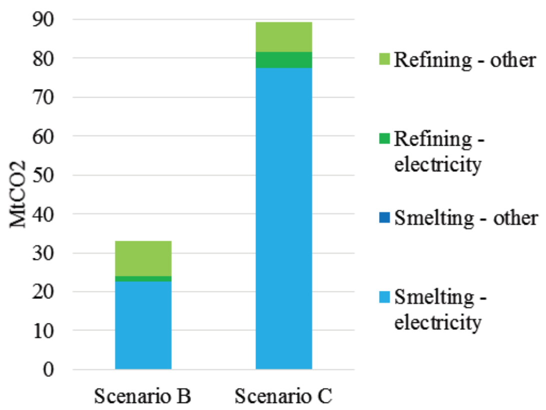


Figure 6: Breakdown of the mitigation potential of scenarios B and C for medium population fertility ($MtCO_2$).

5. Conclusions and Outlook

The production is not expected to decrease in the future as China's more than one billion citizens see their income and welfare rise steadily, which results in unseen demand for aluminium products. Between 1989 and 2009, the in-use stock per capita grew by 693% to reach 58.9kg/capita. This is however still only about 10% of current levels in developed countries like the United States and Japan. The increase in in-use stock will mainly be provided by primary aluminium production, as the existing in-use stock is too small and too young to yield enough recyclable scrap for a sufficing secondary production. Unfortunately producing primary aluminium is much more polluting than recycling it. Chinese factories of primary aluminium emit more than 13 times more CO_2 per kilogram than the world's average CO_2 emissions per kilogram of recycled aluminium.

Besides replacing primary by secondary production, other options offer mitigation potentials, too. As a crucial input for the electrolysis, specific electricity consumtpion and the nature of its generation mix offer the strongest potential – especially in China. Currently many chinese electricity plants are small, of lower grade technology and produce electricity based for 75% on coal. Increasing the industry's concentration, technology level and by replacing coal plants with renewables has a considerable impact on the aluminium industry – and all other electricity intensive industries. The specific electricity density of Chinese primary aluminium smelters, even though world leaving, can still be improved by increasing its concentration, tightening emission and efficiency entry requirements, decreasing electricity bill subsidies and continous engineering.

The refining process also offers mitigation potential, even though it is smaller than the smelting stage. Shifting to cleaner heat sources, increasing the technology level and by improving the bauxite ore quality, substantial emission reductions can be realised. As China's domestic bauxite is of low quality, it will have to import it and increase its dependence on e.g. Australia, currently its main bauxite exporter.

Life Cycle Assessment was previously used by the author to assess environmental impact of secondary aluminium production [18] as well as primary aluminium production at country level [19]. In this paper three future scenarios were developed to assess the Chinese primary aluminium-related CO_2 emissions in 2020, in comparison with 2012. The first scenario (A) is a business-as-usual extrapollation of recent trends while the two other scenarios are simulating low (B) and high (C) mitigation potential. The BAU scenario forecasts the emissions to rise by 52% between 2012-20, or from 383 to 584Mtonnes of CO_2. Scenarios B and C predict a mitigation potential of respectively 33 and 89Mtonnes of CO_2 by 2020.

The mitigation potential is underestimated in these scenarios as they do not take into account certain other emission drivers like enhanced bauxite quality, migration of the smelters towards regions with greener electricity mixes and the gradual substitution of primary production by secondary production. On top of this, other non-CO_2 CO_2eq. emissions are not studied in this paper, but would also decrease due to lower electricity consumption, better electrolysis process control software and further production technology progress. China is hence not expected to decrease its emissions due to primary aluminium production, but through implementing its Five-Year-Plan policies, it can strongly mitigate that increase. A lot of investments need to be done at a national level, both in its electricity production parc as in its aluminium production plants.

Acknowledgments

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